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THESIS

A COMPUTER PROGRAM TO MODEL THE CN^2 OPTICAL TURBULENCE CHARACTERISTICS OF A GIVEN ATMOSPHERE, ITS CONVERSION TO IBM FORTRAN AND UTILIZATION

by

Nicholas J. Padula

JUNE 1985

Thesis Advisor Donald L. Walters

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A Computer Program to Model the Cn² Optical Turbulence Characteristics of a Given Atmosphere, Its Conversion to IBM Fortran and Utilization

by

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ABSTRACT

This thesis describes the conversion of a computer program from Fortran IV used by the CDC computer to Fortran IV compatible with the Naval Postgraduate School IBM 3033 system. The converted program, called TURB2, estimates the magnitude of the refractive index structure parameter, $Cn^2(z)$, for a dry atmosphere in horizontal layers. The altitudes of the layers depend upon the corresponding altitudes of conventional meteorological rawinsonde balloon data. The data input is a formatted file called TURB2 DATAIN and the output consists of the value of dry Cn^2 at each altitude along with a graph of log Cn^2 vs. altitude.

Additional keywords: Subroutines; computer files; [illegible] radiation;

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I wish to extend my gratitude to Dr. VanZandt and Jim Warnock at NOAA's Atmospheric Dynamics Aeronomy Lab in Boulder, Co. for kindly furnishing the program and for answering myriads of subsequent questions and requests. I hope that this project will lead to further co-operation in the future.

I. INTRODUCTION

Many areas of modern technology are concerned with the propagation and distortion of electro-magnetic radiation in the atmosphere. In particular, atmospheric optical turbulence seriously degrades visible light astronomy, satellite photography and laser propagation.

Studying and attempting to predict atmospheric optical index of refraction fluctuations has been going on for a number of years [Ref. 1]. With the ascendancy of modern computer methods during the last twenty years, the predictions have grown significantly in accuracy and commensurately in complexity. R.E. Hufnagel published a model [Ref. 2], in 1974 based on empirical data collected at astronomical observatories. However, it did not consider atmospheric dynamics other than an average wind speed. In 1977, T.E. VanZandt published a new model [Ref. 3]. This model is the most comprehensive and accurate one developed to date and attempts to include actual temperature and wind shear gradients that force the production of optical turbulence.

A. BACKGROUND

The computer code based on VanZandt's model was written by J. Warnock at the National Oceanographic and Atmospheric Administration's Atmospheric Dynamics Aeronomy Laboratory in Boulder, Co. The latest version of the program, that is constantly being updated, has a modular format and consists of twenty subroutines and functions. The code was written to be executed on NOAA's CDC Cyber 750 computer using Fortran IV. The primary concern of this thesis was the

translation of the subroutines as received to code that would be compatible with the Fortran IV used at the Naval Postgraduate School's (NPS) IBM 3033 computer system and to exercise this program on specific atmospheric wind and temperature profiles. Additionally:

1. a main program was written to consolidate the subroutines, read the input data file and print the tabular output,

2. a data processing subroutine was written to transform the raw input data into the variables required in the following subroutines, and

3. a Disspla routine was written to produce a graphical presentation of the computer model output and to permit comparison with whatever reference values were input.

B. GOALS

With the recent interest that the Department of Defense has shown in visible wavelength laser systems, an accurate computer model for atmospheric optical turbulence is essential for meaningful systems analysis. Ideally, this model should be relatively fast and easy to use and should be able to operate with readily available data.

The program that has been developed is capable of satisfying these requirements. The raw input data comes from conventional rawinsonde printouts. These are available in the computer record archives of the National Weather Service for hundreds of stations, ashore and afloat, and going back quite a number of years. The program produces tabular and/or graphical output from the rawinsonde data entered in the data input file (hereafter DATAIN file). For a given location and date, the program estimates the turbulence structure parameter, Cn^2, between each input data altitude.

Because it is rather easy to use, it is hoped that the program will prove to be beneficial for physical meteorology and laser technology classes. It is also very instructive to modify the input data to determine the effects of several atmospheric variables upon the turbulence structure parameter. For example, it is possible to determine the effect of variations in the temperature or wind shear profiles upon the final output.

The program should be useful as a reference to researchers who are trying to measure the Cn^2 profile experimentally. Assuming the availability of a nearby rawinsonde launch site (within 50 to 100 miles), the computer model will produce Cn^2 estimates for comparison with experimental data. Ideally the experimental measurement device or the model will be fine-tuned as a result of detailed comparative analyses.

Finally, the program also has the potential to be used as a subroutine to estimate the Cn^2 profile for other programs. For example, the G.U.T.S. program presently used in AE-4706 makes use of a rather crude approximation for Cn^2. Using the much more realistic values obtained from this computer model would serve to improve the accuracy of the G.U.T.S. output.

The primary goal of my work was to translate the CDC code into a smoothly running and error-free program for the IBM system at NPS. Also, the format of the program as received, was somewhat rough and required a significant amount of time to understand and be able to use. As a secondary goal then, it was desired to make the program as 'user friendly' as possible so that it could be used for class projects and by researchers with a minimum of instruction and difficulty. Finally, since the Cn^2 parameter can vary erratically with altitude, it was thought that simple tabulated output would be of limited utility, especially as

an instructional aid. Therefore a graphical presentation capability was desired. Additionally, it is quite likely that a researcher using the program would find it useful to be able to compare several profiles, perhaps obtained by different methods. Thus the capability to read several data files and plot the ccmparative data was also incorporated in the program.

II. APPROACH TO PROBLEM

The model program was received from NOAA in printout form and was typed onto my 'A disk on the NPS system with each subroutine filed as a separate Fortran program. During this phase, it became evident that the full 60 bit capability of the CDC computer had been utilized . To achieve a comparable level of accuracy on the IBM system, it was necessary to use double precision. Rather than change all the variables to double precision before more familiarity was gained with the program, it was decided to use the autodbl function which would automatically change all the variables and functions to IBM double precision. Mr. Hilleary at the computer center was most helpful in this endeavor.

Because of the complexity of the program and its modular structure, it was decided that a ground-up module test method would prove most advantageous. Thus once all the subroutines were copied and checked, a short WATFIV program was written around each subroutine to test its correct operation. The WATFIV compiler was utilized because of its excellent error messages. Each program supplied the required input variables, called the respective subroutine and displayed the desired variables which were spot-checked using a handheld calculator. During the initial parts of this phase, no attempt was made to integrate the subroutines, i.e. each program tested one subroutine or function only, in an attempt to minimize the amount of debugging required. However, once all the subroutines had been tested individually, some integrated testing was conducted. The modular testing procedure additionally served as an excellent means of gaining familiarity with each part of the

program. This proved to be of great benefit in later stages of debugging and modification.

Simultaneous with the testing and debugging process, it was realized that actual rawinsonde data would be required once the program was ready to run. To avoid a lag in the development, an effort was made to procure some representative data fairly early. The dates and locations were chosen to coincide with a detailed experiment run by the University of Arizona and the Air Force [Ref. 4] at Sunset Canyon, Az. and Truckee, Nev. in 1977-78. The Naval Environmental Prediction and Research Facility (NEPRF), located in Monterey, Ca., provided rawinsonde data upon letter request. The rawinsonde data output was in the form of raw tabulated values for the mandatory and significant reporting levels and a summary table which listed the desired variables including atmospheric pressure, temperature, humidity, wind speed and direction and absolute altitude. Additionally graphs were also received but were not utilized. The summarized values were filed in the proper format in the DATAIN file.

The next step was to write a data processing subroutine that would: 1. process the raw data into the units required by the subroutines and, 2. calculate the necessary derived variables such as the humidity gradient and the wind shear.

With the completion of the data processing subroutine, all was in readiness for the development of the main program. The function of the main program was to step the calculations from the first data input set (corresponding to the lowest slab of a given atmosphere) sequentially through each slab until the last data set was reached. The main program also initialized a number of common variables that were used in various subroutines throughout the program. Lastly, it served as a framework for the proper sequencing of the subroutine calls.

As might be expected in complex programs, even with the extensive modular testing previously conducted, a significant amount of debugging was required once the program was finally integrated. When attempts to decipher the Fortran error messages proved fruitless, the WATFIV compiler was again utilized. The main difficulty in debugging was trying to trace the errors through a series of imbedded subroutines. For example one of the most difficult problems to detect at this point was caused by an underflow error. The EXPNX function was written to prevent underflow or overflow errors from occurring. As received, it tested to see if variables exceeded the limits of the CDC computer (approximately 1.E±300). During the early testing, it was realized that these limits would have to be changed to correspond to IBM system 3033's capacity (approximately 1.E±75). If the variable in question exceeded these limits, the function EXPNX would revalue the variable to the respective limit imposed by the computer. What was not immediately apparent however, was that the corrected variable was subsequently multiplied by another small number (on the order of 1. E-3) in another subroutine which ultimately caused the underflow. While in itself, the error was relatively easy to detect, it proved difficult and time consuming to trace since the offending subroutine was buried in other subroutines.

One technique that also proved effective was to draw a large flowchart which listed each subroutine and function contained in the program. Additionally each subroutine or function was annotated with the other subroutines that called it as well as those that were called by it. This was very useful in: 1. gaining the 'big picture' of the structure of the program, 2. checking that the required variables were indeed entered or printed and that each was listed in the call statement, 3. detecting several variables that had inadvertently undergone name changes in the

genesis of the program at NOAA and had subsequently become sources of confusion in the translation, and 4. tracing suspect variables back to their origin.

III. SOLUTION

A. THEORY

VanZandt et al, [Ref. 3], assume the existence of thin horizontal layers of turbulence in an otherwise non-turbulent atmosphere. These layers are evident in radar [Ref. 3] and direct balloon measured Cn^2 profiles, [Ref. 5] and [Ref. 6]. They vary with time and location, though they are generally of limited horizontal area. The large scale turbulent eddies in this thin region are inherently inhomogeneous, anisotropic and non-steady. Nevertheless, within the turbulent layers, the turbulence approaches homogeneous and isotropic conditions if the scale length is taken small enough (i.e. scale lengths much shorter than the thickness of the layer). Furthermore, it is assumed that all the different sized eddies come into existence within a short time span, relative to the life span of the turbulent eddy itself. With these approximations, the velocity fluctuations can be considered to be steady-state and the turbulence structure parameter, Cn^2, can be estimated for the turbulent layer. To estimate the turbulence throughout an entire vertical shaft of atmosphere, it is also necessary to estimate the fraction, F, of the entire shaft that is turbulent. The calculation and combination of these two estimates form the basis for this model and the program.

For the case of homogeneous, isotropic turbulence, Tatarski [Ref. 1], estimates Cn^2 by;

$$Cn^2 = a^2 \bullet \alpha' \bullet L_o{}^{4/3} \bullet M^2 \qquad (3.1)$$

where a is a universal constant generally taken to be 2.8, α' is the ratio between the eddy viscosity and the eddy thermal diffusivity generally taken to be 1.0, L_o is the outer scale length of the turbulence and M is the vertical gradient of the refractive index.

L_o is assumed to be of the order of the thickness of the turbulent layer itself. An expression for L_o, also given by Tatarski, is;

$$L_o = (e / S^3)^{1/2} \tag{3.2}$$

where e is the dissipation rate of turbulent kinetic energy and S is the vertical gradient in the horizontal wind velocity (i.e. $\partial \vec{V} / \partial z$). Rather than try to measure these values, the developers of this model selected a value of L_o that would normalize the theoretical Cn^2 to that produced by their experimental radar measurements. This value of L_o turned out to be 10 meters.

The expression for M is given by [Ref. 3] as;

$$M = -77.6 \bullet 1.E^{-6} \bullet (p \bullet \partial \ln\theta / T \partial z) \bullet (1 + 15500\, q/T \bullet [1 - .5 (\partial \ln q / \partial z) / (\partial \ln\theta / \partial z)] \tag{3.3}$$

where p is the atmospheric pressure in millibars, T is the absolute temperature in Kelvin, θ is the potential temperature in Kelvin, q is the specific humidity and z is the altitude in meters. To calculate M, the vertical resolution of the meteorological data should be on the order of the layer thickness, L_o. Current rawinsonde measurements are somewhat coarser, on the order of 100 meters (for routine equipment, special equipment is available which is capable of producing a much finer dataset), however the rawinsonde data is frequently the best data available. Using eqns. (3.3) and (3.1), it is possible to estimate the value of Cn^2 in the turbulent layers from routine rawinsonde data.

A slab of atmosphere on the order of 10 meters thick will usually contain at least one set of turbulent and non-turbulent layers. Having previously estimated the value of Cn^2 in the turbulent layer, the average Cn^2 for slab i is;

$$\overline{Cn^2(i)} = Cn^2(i) \bullet F(i) \qquad (3.4)$$

where F(i) is the mean fraction of slab(i) that is turbulent. There are no expressions to solve for F directly so a statistical distribution is used.

First one calculates the wind shear, which is the difference between the horizontal wind velocity vector at two consecutive altitudes (note that any vertical wind component, such as due to convective flow, is neglected). At any point, the total shear, St, can be thought of as being composed of two parts, the mean shear, Sm, and a fluctuating part, Sf. Then at any point;

$$St = Sm + Sf \qquad (3.5)$$

The coarseness of the rawinsonde measurements will provide sufficient accuracy for the calculation of Sm, but will preclude the direct calculation of Sf which would require the separation of data points to be on the order of several meters. Thus it was assumed that Sf has a Gaussian distribution Z( ) and a standard deviation, sigma, which is independent of Sm so that;

$$Z\ (Sf/sigma) = \exp(-Sf^2/2 \bullet sigma^2)\ /\ (2 \bullet pi)^{1/2} \qquad (3.6)$$

Then the probability, f, of a total shear in the increment St to St + dSt is;

$$f(St)\ dSt = Z[\ (St-Sm)/sigma\ ]\ d(St/sigma) \qquad (3.7)$$

It was also assumed that a region is turbulent only if St exceeds a critical shear, Sc. Then F is given by;

$$F(|\text{taucrit}|,|\text{taumean}|) = \int_{-\infty}^{-|S_c|} f(St)\,dSt + \int_{+|S_c|}^{+\infty} f(St)\,dSt \qquad (3.8)$$
$$= P(-|\text{taucrit}|-|\text{taumean}|) + Q(|\text{taucrit}|-|\text{taumean}|)$$

where |taucrit| = |Sc|/sigma, |taumean| = |Sm|/sigma, P( ) is the cumulative distribution function of Z( ) and Q( ) = 1 - P( ). Thus, F varies with |taumean|, the magnitude of the wind shear and inversely with |taucrit|, the atmospheric stability.

From eqn. (3.8), F is a function of two variables, taucrit and taumean, which in turn are functions of three variables, Sc, Sm and sigma. Sm, as mentioned, is computed from the rawinsonde data. Sc is calculated from;

$$Sc = [\ (g \bullet \partial \ln \theta / \partial z)\ /\ Rc\ ]^{1/2} \qquad (3.9)$$
$$= 2(\ g \bullet \partial \ln \theta / \partial z\ )^{1/2}$$

The critical value for Richardson's number, Rc, for the onset of turbulence is taken to be .25 and this value was substituted in the second equality of eqn. (3.9). The value of sigma is taken as .01/s in the troposphere and .015/s in the stratosphere, [Ref. 3]. Fith these variables in hand, F(i) for each slab can be calculated from eqn. (3.8) and ultimately Cn^2 from eqn. (3.4).

B. METHOD

The program as received was similar to IBM Fortran IV overall, although there were some significant differences. The CDC to IBM Conversion Guide, [Ref. 7], proved most helpful as did the staff at the Computer Center and local expertise in the Aeronautical Engineering Dept. at NPS. The

most frequent modifications that were made have been listed in Table 1 .

TABLE 1

CDC to IBM Translation

Item	CDC code	IBM translation
Comment card	uses * or C	substitute C for * in col. #1
Continuation card	uses '1' in col. #6	substitute * for 1
Statement separation	uses A=1$B=2$C=3 for example	write each statement on different lines, i.e. A=1 B=2, etc.
Initialize statements	uses A=B=C=0	write each statement or equality on different lines, i.e. A=0 B=0, etc.
Program statements	uses Program statement at the start of the main subroutine	delete Program statement
Name length of variable	permits up to 7 characters in name	rename variables so that maximum length doesn't exceed 6 characters
Name length of subroutine	same as above	same as above
Delimiters	uses PRINT"ABC" for example	substitute ' in place of "
Print statements	uses PRINT*A,B,C or PRINT 100,X	substitute WRITE(6,100)X as required
Integer division	uses LAST=NQUAD/2 where LAST and NQUAD are integers and NQUAD is odd	rewrite using different approach

Once the program was running satisfactorily, the Disspla graphics routine was developed. Since the program was written as single precision and then converted into double

precision through the use of the autodbl function, all of the output values were necessarily of double precision type and it was impossible to selectively override the function so as to declare some of the variables as single precision. Because Disspla will not accept double precision, two alternatives presented themselves at this point, either; 1. write a separate, single precision plotting program that would read the main program's data output file (hereafter the DATAOUT file), as single precision, and plot the values or, 2. convert the entire program to double precision except for two single precision variables which would serve as the x and y coordinates for the Disspla routine. Since the program for alternative #1 was already working, it seemed the most expedient choice and therefore a separate, short plotting program was developed. Once it was running however, it became apparent that having to run first one program and then another was overly cumbersome, especially for a program to be made available for general use. Alternative #2 was then developed, i.e. all the program variables were declared as REAL*8 except for two single precision, dummy variables, PLOTAX and PLOTAY, and the plotting routine was incorporated as a section of the main program. This proved very effective because the user now received the graphics at a Tektronics 618 terminal followed by the tabulated data in a DATAOUT file which is available for browsing or printing from the user's Filelist (FLIST).

C. INITIAL CALCULATIONS

The main program first declares all the variables and initializes the necessary constants which are used in the program and reads the program options (i.e. whether or not a plot is desired as well as the number of runs desired). Next the program reads the number of data sets, N (i.e. the

number of levels reported by the rawinsonde), from the DATAIN file. The variable format is I5. Following that a 'Do loop', iterated N times, reads the data sets from the DATAIN file. For each level, the data set format is 5(F10.5), F10.2 and the variables are in the following order: pressure (millibars), temperature (Celsius), relative humidity (%/100), wind speed (meters/ second), wind direction (compass heading in degrees relative to true North) and absolute altitude (meters). The respective variable names are: PRESS, TEMP, HUMID, WS, WD, and Z.

The data processing subroutine (DATPRO) is called with these six variables plus N. The subroutine calculates;

TEMPA (the absolute temperature, TEMP + 273.)

THKARY (the thickness of the slab, Z(I+1)-Z(I))

DQDZRY (the average gradient of the humidity through the slab)

PARY (the weighted average of the pressure for the slab)

TARY (the weighted average of the temperature for the slab)

QARY (the weighted average of the humidity for the slab)

PARY, TARY and QARY were originally taken as simple averages, but were changed to weighted averages in order to smooth the roughness introduced when point rawinsonde values are used for continuously varying (spatially and temporally) physical parameters. The generic weighting equation used was;

$$X(I) = [\ Y(I-1) + 3.\bullet Y(I) + 3.\bullet Y(I+1) + Y(I+2)\ ] \ /\ 8. \tag{3.10}$$

The value of THETA, the potential temperature, is calculated next from;

$$THETA(I) = [(PRESS(1)/PRESS(I))**(R/C_p)]\bullet TEMPA \qquad (3.11)$$

where R is the gas constant and C_p is the specific heat.

The wind vector is then broken down into the usual u and v components (UX and UY respectively) and the wind shear is calculated from;

$$SHEAR(I) = [\ (UX(I+1) - UX(I))^2 + (UY(I+1) - UY(I))^2\ ]^{1/2} / THKARY(I) \qquad (3.12)$$

Next, the stability parameter, STBARY, is calculated by;

$$STBARY(I) = G\bullet[\ LOG(THETA(I+1))-LOG(THETA(I))\ ] / [Z(I+1)-Z(I)] \qquad (3.13)$$

Finally Richardson's number, RIARY, for the slab is calculated by;

$$RIARY(I) = STBARY(I) / (SHEARY(I))^2 \qquad (3.14)$$

The values of TARY, PARY, QARY, STBARY, SHEARY, DQDZRY, RIARY and THKARY are all arrays with N-1 elements. These arrays are returned to the main program. The primary 'Do loop' of the main program, which iterates over the altitudes corresponding to the input data, then calls the subroutines SHRSGM, STBSGM and INTLGS. INTLGS calls each of the remaining subroutines and functions. A flowchart, Figure 3.1, depicts the general flow within the program. Rather than describe each subroutine, a brief summary of each is included as Appendix B.

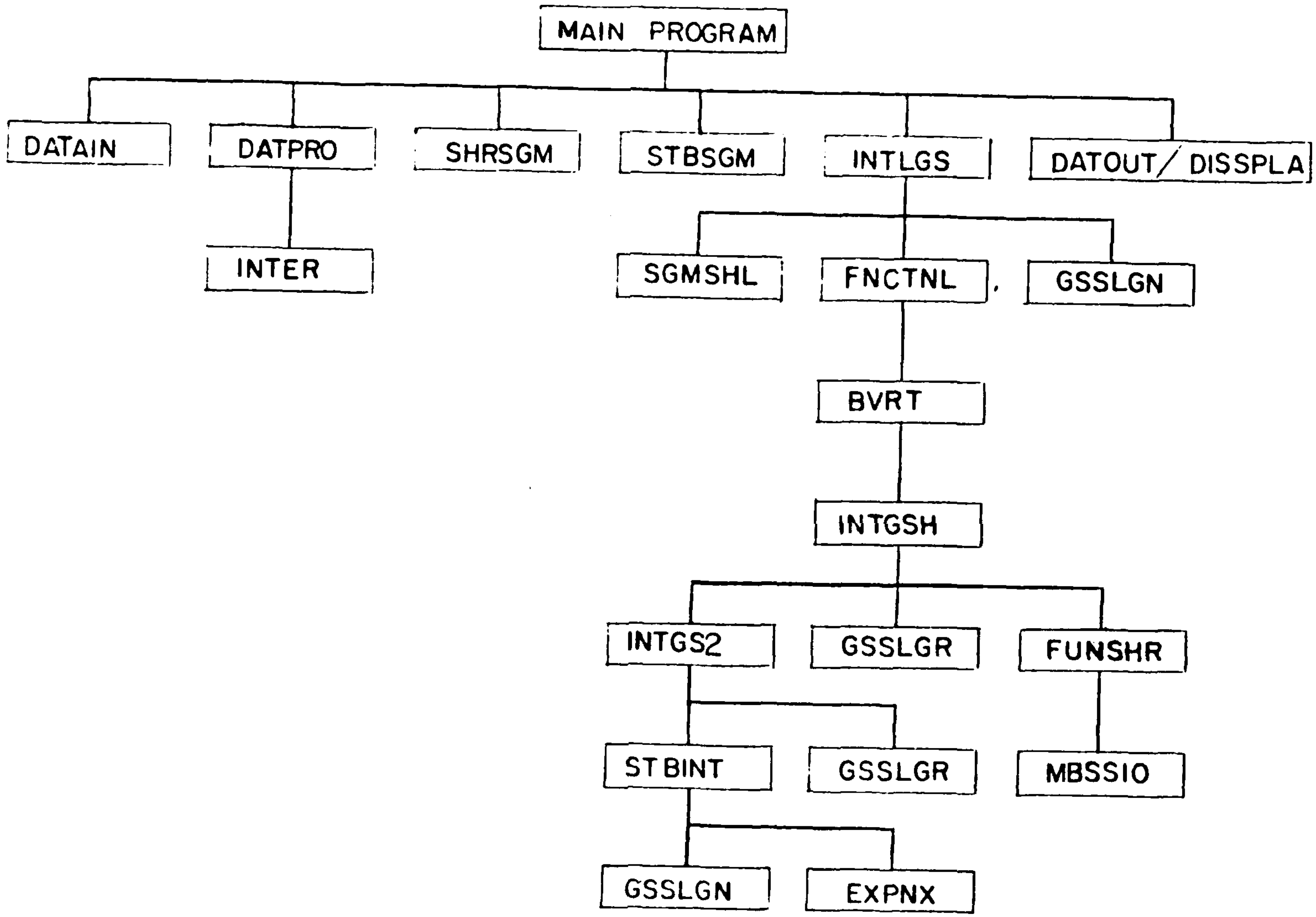

Figure 3.1 Subroutine Flowchart

The end product is the value of PCNSQ (or Cn^2) calculated for each slab. The average altitude of the slab, MIDALT, is used for the graph and tabulation. The Cn^2 values with the corresponding MIDALT's are stored in two N-1 element, single precision arrays, PLOTAX and PLOTAY respectively. At this point, if the number of runs is specified as '2' in the DATAIN file, the program reads in all the datasets again and recalculates the Cn^2 profile (this option will be further discussed in Chap. 4). Next, if specified (i.e. if PLOT = '2' in the DATAIN file), the Disspla routine is invoked which plots the value of log Cn^2 on the x-axis vs. MIDALT on the y-axis. The graph displayed is available in hardcopy form at the Tektronics 618 terminal. Finally, the Cn^2 and MIDALT values are also listed in the TURB2 DATAOUT file which has been transferred to the user's 'A' disk. This file may then be browsed or printed as desired.

D. INPUT FORMAT

The following section describes the step-by-step procedure to be followed when executing TURB2. Prior to execution of course, it is necessary to obtain copies of the required programs, namely TURB DATAIN, TURB2 FORTRAN and optionally, REFPLOT DATAIN. Additionally, an exec, TURB2 EXEC, is available and is very convenient to use.

The first step is to type the rawinsonde data into the TURB DATAIN file. The easiest method is to copy, rename and write-over an old DATAIN file (see Appendix A), however the format is listed in Table 2 .

When the rawinsonde data is received, each data set (i.e. a set of all the measurable variables at a given altitude) will fall into one of three categories, either;

1. the dataset has balloon measured data (pressure, temperature and humidity along with radar altitude) but

TABLE 2

TURB DATAIN File Format

Card (s)	Cols.	Type	Variable	Remarks
1	20	I5	PLOT	enter '1' if a plot is desired, '2' if not
2	20	I5	#RUNS	enter the number of runs desired (1 or 2)
3	16-20	I5	N	number of datasets to be entered
4->N+4	1-10	F10.5	PRESS	atmospheric pressure (millibars)
"	11-20	F10.5	TEMP	temperature (degrees Celsius, not absolute)
"	21-30	F10.5	HUMID	relative humidity (%)
"	31-40	F10.5	WS	wind speed (meters/sec)
"	41-50	F10.5	WD	wind direction (compass direction, degrees)
"	51-60	F10.2	Z	absolute altitude (meters)

Note: If #RUNS = 1, the DATAIN file is complete. If #RUNS = 2, copy cards 3 thru N+4 and insert them immediately following card N+4 (see Appendix A).

is missing the ground radar generated data (wind velocity),

2. the radar wind speed and direction data appears but the balloon data is missing, or

3. all data is recorded (at the 7 or 8 mandatory levels only).

Typically, either balloon or radar data is taken at 80 to 100 points.

Note that the Datain file and the program accept only complete data sets. Enter a value of '999.9' for any data points that are missing. The program will then do a semi-log interpolation for the missing values using one of two methods as follows;

1. if #RUNS = 1, all the missing values are assigned interpolated values. In this case, the program calculates, plots and tabulates only one Cn^2 profile or

2. if #RUNS = 2, the program rereads the raw datasets and interpolates only for missing values of WS and WD. Thus those datasets missing PRESS, TEMP and HUMID are deleted. In this case, a new Cn^2 profile is estimated, which is plotted and tabulated in addition to the previous one (i.e. when #RUNS = 1). Setting #RUNS = 2 nearly doubles the number of executions and thus the run time. The use of this option will be discussed in Chap. 4.

The program may now be compiled (if necessary) and executed, it does not require batch processing and the output should be ready within several minutes. Note that it is possible to store many data sets in one's file, but the TURB2 EXEC reads from TURB DATAIN. Thus the user may find it necessary to either rename his/her DATAIN file or change the EXEC.

If the user wishes to display a second Cn^2 plot simultaneously with the model's estimated plot, the values for the second plot are stored in a second DATAIN file called REFPLOT DATAIN. This is not the same as setting #RUNS = 2. In this case a previously measured or estimated Cn^2 profile is input and the program merely plots the input values. As in the previous case, the easiest method is to copy and rewrite an old file, however the format is as follows:

TABLE 3

Reference Plot Datain File Format

Card (s)	Cols.	Type	Variable	Remarks
1	20	I5	M	number of data points to be plotted
2->M+1	1-10	E10.4	Cn^2	reference values of Cn^2 for comparison (not log values)
"	11-20	F10.2	Alt	absolute altitude corresponding to value of Cn^2

IV. RESULTS

A. COMPARISON

Once the program was debugged and executing reliably, it was necessary to compare the output to that produced by the original program at NOAA. This procedure served as an acceptance test to validate the operation of the translated program. To this end, a random input and output dataset was requested from NOAA. When the translated program was run with the test input on the NPS computer system, the output was found to agree closely with output produced by the original code executed on NOAA's CDC computer (see Tables 4 and 5, Appendix D). Table 4 was produced using the first method described (i.e. #RUNS = 1) while Table 5 was produced using the second.

As can be seen from Figure 4.1 and Table 4, when the first interpolation method was used (i.e. interpolated values are substituted for all missing datapoints), there are noticeable disagreements, but overall the IBM output is within 17.9% of the NOAA results (if one neglects the large spikes). The difference in the accuracy between low and high altitudes was insignificant. There is one large excursion around 15 km. that is without explanation. Also, there were several spikes in the NOAA data at 2 km. and at 6.3 km. that seem suspect and were not repeated in the IBM output.

As can be seen from Figure 4.2 and Table 5, when the second interpolation method was used (i.e. interpolated values are substituted for datasets missing WS and WD only, with the other datasets being deleted), the output tended to be in closer agreement with the NOAA results. However, in several areas, the IBM data tended to respond more slowly

LOG CN**2 VS. ALTITUDE

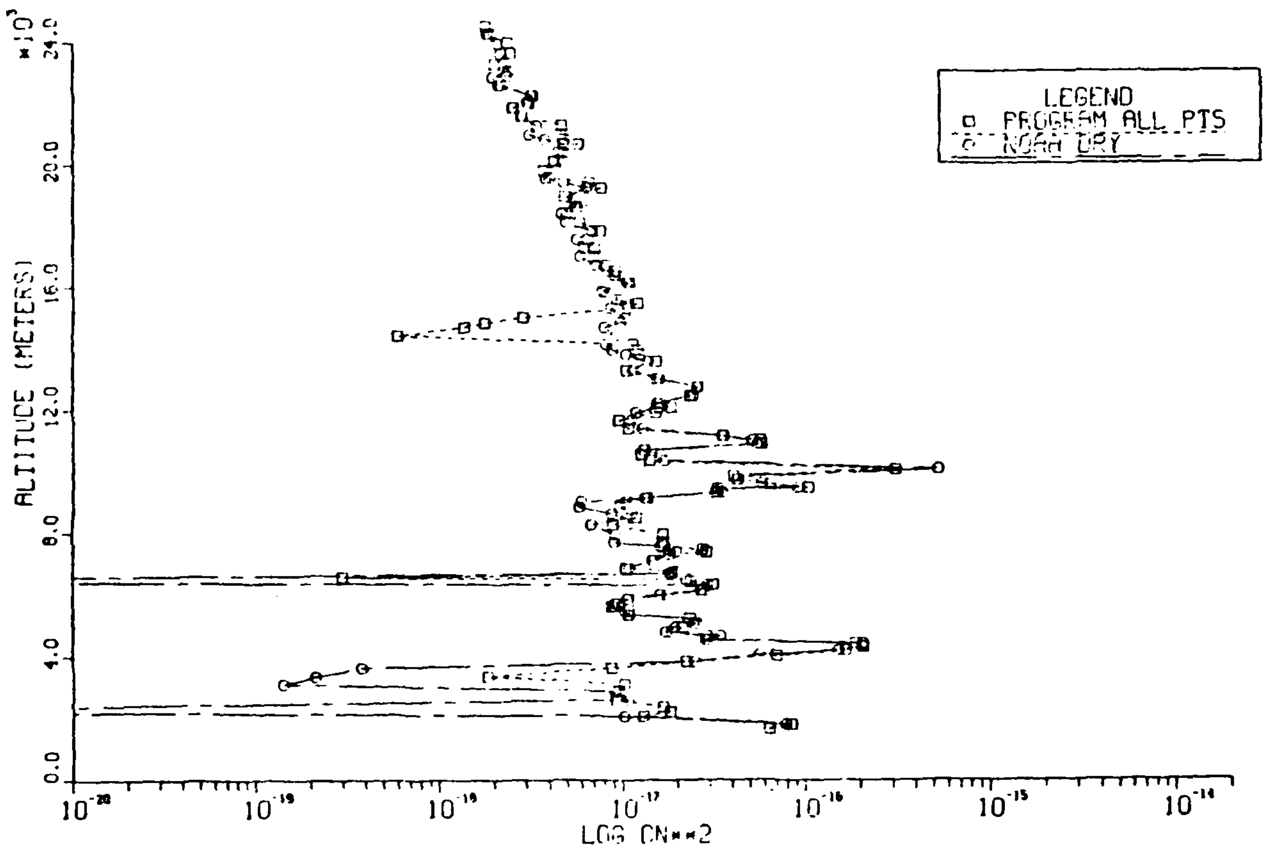

Figure 4.1 Comparison of Results, #RUNS = 1

LOG CN**2 VS. ALTITUDE

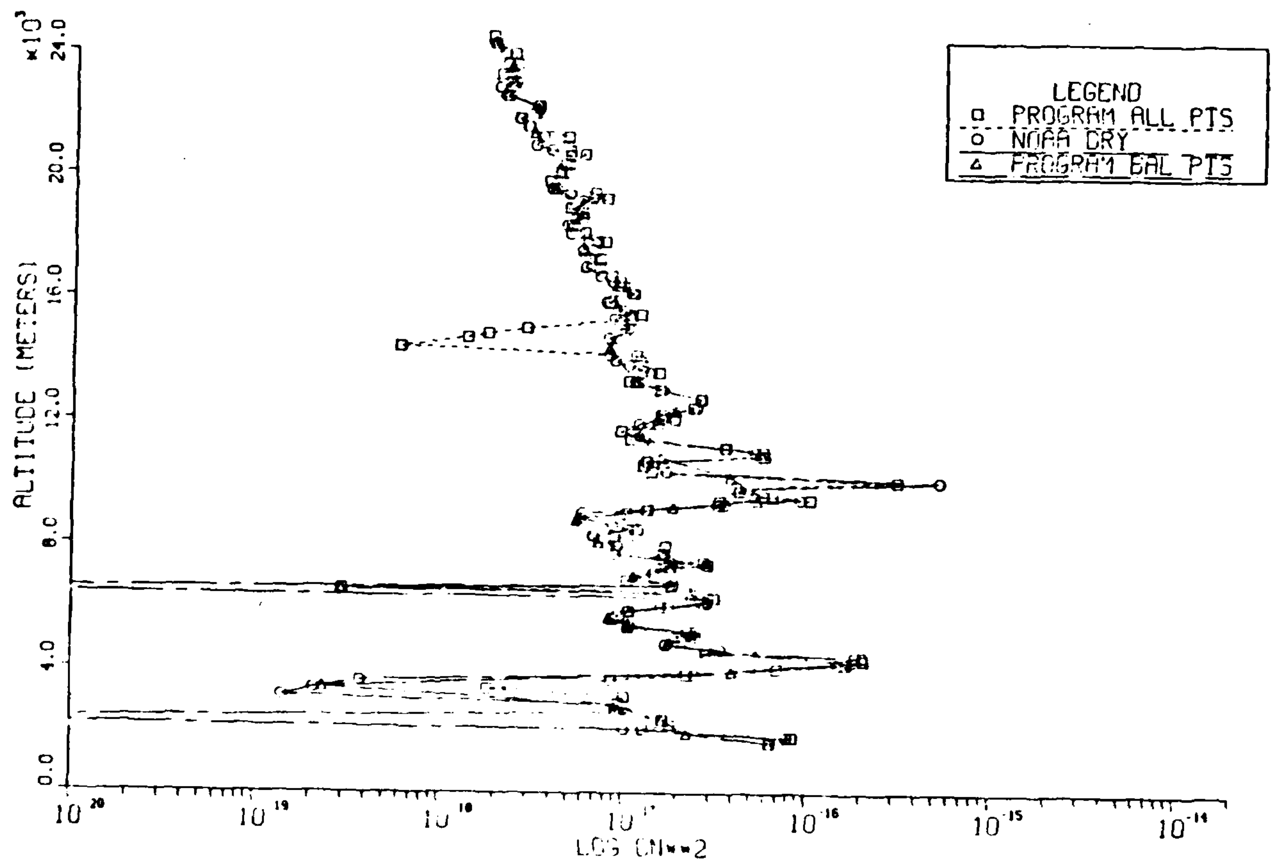

Figure 4.2 Comparison of Results, #RUNS = 2

than the NOAA results (because of the fewer datasets) and some of the spikes in the NOAA data were 'smoothed' into insignificance. The underlying question is whether the resolution of the rawinsonde data is sufficient to predict the variations in the value of Cn^2 at the scale shown or conversely, is the data being overprocessed to the point that the spikes are merely 'noise'. To answer the question, it will be necessary to process more datasets and also to measure the Cn^2 profile experimentally so that comparisons can be made.

Overall, with #RUNS = 2, the IBM output was found to be within 14.7% of the NOAA results. In the region below 12 km., the agreement was within 20.1% of the reference data. The spike at 6575 meters seems to be produced by a glitch in the program (because the wind shear is zero for several consecutive slabs) and probably doesn't predict the actual Cn^2 accurately. Above 12 km., the agreement is excellent, averaging 5.0% and without any significant excursions.

There are two primary reasons why the output doesn't agree exactly, as one might expect. The first is due to the fact that the data processing subroutine used in the NOAA program was not received with the rest of the code and thus a substitute had to be written. The original (i.e. NOAA) data processing routine was received later with the comparison test data. Although the two are very similar, there are some differences and thus slightly different values are input to the main program in each case. The second reason is that the NOAA program has undergone some modifications in the time between the receipt of the original code (from which the IBM code derived) and the receipt of the comparison test data. While it is highly unlikely that any large differences would be introduced by the modifications, it is almost certain that some small differences crept in. Since the NOAA program itself is still undergoing development, it is impractical to try to keep current translated copies.

However, with these differences in mind, the output of the translated code is quite satisfactory for the purposes specified and has the potential for being much superior to the accuracy of any of the previously available models. Also the ease of operation and useful graph/ tabular output format make it a very practical and useful addition to the NPS library.

V. CONCLUSIONS AND RECOMMENDATIONS

The NOAA program differs primarily in the smoothing algorithm used that produces a different dataset for the main program. The translated program was modified so that a comparison could be made between the two methods of data processing described earlier. The intent of the comparison was to see if the first method was actually more accurate or if the larger number of datasets only tended to increase the 'noise'.

While the results indicated that the first method is better, it is difficult to make a judgement based on the results of a single dataset. However, for routine use, the first method is recommended (i.e. set #RUNS = 1 in the DATAIN file).

One of the strengths of this model is that it requires only readily available rawinsonde data to be input, but that simplicity is also a basic source of error that may occur in three forms.

The first error comes about because the rawinsonde data, while available for a great many locations and times, is not available for all places and times. If one wishes to compare the model predictions with measurements from a radar or scintillometer, it is necessary to assume that the atmospheric parameters recorded by the rawinsonde are approximately equivalent to those present at the measurement site. This may or may not be a reasonable assumption because of the spatial or temporal variation in the parameters. For short distances (less 100 miles and without large variation in geographical features like mountains or oceans), and times (2-4 hours depending on the time of day), the assumption is probably reasonable. Obviously, as distance or time

from the observation point increases, less correlation between the model and the measured data are expected.

The second error derives from the fact that scintillometer measurements are time averaged line integrals, whereas the rawinsonde balloon carries an array of point sensors. Also the balloon rises over a one to two hour period along an oblique path as a function of the wind velocity, while the experimental measurements are usually made along a vertical one. For these last two reasons, even if the balloon launch site and the radar or scintillometer were co-located and readings were made simultaneously, there would still be some residual data errors.

The third source of error occurs only if there are convective layers present in the atmosphere. Because of the difficulty in modeling the effects of such layers, the present model neglects them.

With these limitations in mind, the model is still the best available and should be of utility to those whose research requires the estimation of $Cn^2(z)$. As the parent program continues to be improved, it may be worthwhile at some future time to add the corresponding updates to this version also. Additionally, I think that the program could be integrated into a propagation model, such as G.U.T.S., for a significant increase in accuracy over the present model.

APPENDIX A
TURB DATAIN FILE FORMAT EXAMPLE

This appendix contains the dataset used for the comparison test. It is also to be used as an example of the format required by the main program. Note that the file contains two copies of the same dataset. This is the format used when #RUNS = 2. If only one run is desired, the repeated dataset may de deleted (i.e. there would only be 118 lines vice 236).

```
      PLOT?         1     (1-yes, 2-no)
      #RUNS   =     2     (1 or 2 only)
 # DATA SETS  =   118
 PRESS.     TEMP.     HUMID.     WS       WD        ALTITUDE
(mbars)     ( C)     (%/100)   (m/s)   (degrees)   (meters)
  834.9      22.4      .291       4.1     120.        1610.
  828.0      20.2      .261     999.9     999.9       1680.
  999.9     999.9     999.9       5.1     158.        1930.
  778.0      15.5      .357     999.9     999.9       2200.
  999.9     999.9     999.9       4.6     164.        2240.
  750.0      12.0      .424     999.9     999.9       2520.
  999.9     999.9     999.9       5.1     173.        2670.
  700.0       6.9      .575     999.9     999.9       3100.
  999.9     999.9     999.9       5.1     176.        3140.
  999.9     999.9     999.9       5.1     186.        3560.
  648.0        .8      .883     999.9     999.9       3720.
  999.9     999.9     999.9       6.7     212.        3930.
  615.0      -3.1      .963     999.9     999.9       4140.
  999.9     999.9     999.9       7.7     243.        4230.
  596.0      -4.2      .690     999.9     999.9       4390.
  999.9     999.9     999.9       7.7     268.        4460.
```

579.0	-6.1	.714	999.9	999.9	4620.
999.9	999.9	999.9	7.7	279.	4680.
999.9	999.9	999.9	7.7	278.	4900.
554.0	-8.5	.664	999.9	999.9	4960.
999.9	999.9	999.9	7.2	274.	5140.
529.0	-10.1	.372	999.9	999.9	5320.
999.9	999.9	999.9	6.7	276.	5410.
513.0	-12.1	.411	999.9	999.9	5550.
999.9	999.9	999.9	6.7	280.	5690.
500.0	-13.8	.619	999.9	999.9	5750.
999.9	999.9	999.9	6.7	275.	5980.
483.0	-16.0	.532	999.9	999.9	6010.
999.9	999.9	999.9	5.7	266.	6260.
460.0	-17.2	.054	999.9	999.9	6380.
999.9	999.9	999.9	4.6	256.	6490.
452.0	-18.8	.304	999.9	999.9	6510.
444.0	-20.1	.492	999.9	999.9	6640.
999.9	999.9	999.9	4.6	256.	6740.
437.0	-20.7	.204	999.9	999.9	6760.
999.9	999.9	999.9	5.1	257.	6980.
410.0	-24.5	.247	5.1	270.	7230.
402.0	-25.5	.555	999.9	999.9	7370.
400.0	-25.7	.417	999.9	999.9	7410.
999.9	999.9	999.9	4.1	278.	7510.
389.0	-27.0	.041	999.9	999.9	7610.
999.9	999.9	999.9	3.6	266.	7800.
999.9	999.9	999.9	4.6	274.	8120.
999.9	999.9	999.9	4.6	270.	8430.
340.0	-35.2	.242	999.9	999.9	8560.
999.9	999.9	999.9	5.7	259.	8720.
999.9	999.9	999.9	6.2	264.	8990.
316.0	-39.7	.314	999.9	999.9	9070.
999.9	999.9	999.9	6.2	271.	9230.
300.0	-42.0	.000	999.9	999.9	9420.
999.9	999.9	999.9	8.2	280.	9470.

296.0	-42.6	.000	999.9	999.9	9510.
999.9	999.9	999.9	11.3	285.	9680.
283.0	-41.9	.000	999.9	999.9	9810.
999.9	999.9	999.9	14.4	283.	9930.
999.9	999.9	999.9	21.6	279.	10220.
999.9	999.9	999.9	23.2	281.	10500.
250.0	-46.0	.000	999.9	999.9	10650.
999.9	999.9	999.9	21.6	282.	10770.
237.0	-48.5	.000	999.9	999.9	11000.
999.9	999.9	999.9	24.7	278.	11020.
999.9	999.9	999.9	26.8	273.	11280.
999.9	999.9	999.9	27.3	271.	11540.
999.9	999.9	999.9	26.8	271.	11790.
999.9	999.9	999.9	27.3	273.	12050.
200.0	-53.5	.000	999.9	999.9	12100.
999.9	999.9	999.9	25.2	273.	12320.
185.0	-55.8	.000	22.7	269.	12600.
999.9	999.9	999.9	25.7	266.	12880.
999.9	999.9	999.9	27.8	264.	13160.
999.9	999.9	999.9	27.3	262.	13430.
999.9	999.9	999.9	25.2	263.	13710.
150.0	-56.3	.000	999.9	999.9	13930.
999.9	999.9	999.9	24.7	265.	13990.
999.9	999.9	999.9	24.2	264.	14280.
999.9	999.9	999.9	25.7	263.	14570.
130.0	-59.6	.000	999.9	999.9	14830.
999.9	999.9	999.9	24.7	262.	14860.
999.9	999.9	999.9	23.2	264.	15160.
999.9	999.9	999.9	22.7	264.	15470.
117.0	-58.0	.000	999.9	999.9	15500.
999.9	999.9	999.9	20.6	264.	15730.
108.0	-59.4	.000	19.0	265.	16000.
999.9	999.9	999.9	17.0	259.	16300.
100.0	-58.3	.000	999.9	999.9	16480.
999.9	999.9	999.9	16.0	266.	16590.

999.9	999.9	999.9	14.4	264.	16870.
999.9	999.9	999.9	13.9	264.	17150.
999.9	999.9	999.9	13.4	269.	17430.
999.9	999.9	999.9	12.4	270.	17710.
999.9	999.9	999.9	10.3	266.	17980.
999.9	999.9	999.9	9.8	266.	18260.
999.9	999.9	999.9	9.3	266.	18540.
70.0	-61.0	.000	999.9	999.9	18710.
999.9	999.9	999.9	8.2	257.	18820.
999.9	999.9	999.9	8.2	261.	19100.
999.9	999.9	999.9	5.7	266.	19380.
62.0	-58.2	.000	999.9	999.9	19470.
60.0	-58.5	.000	4.6	262.	19670.
999.9	999.9	999.9	4.1	266.	19960.
999.9	999.9	999.9	4.6	290.	20240.
999.9	999.9	999.9	6.7	301.	20520.
999.9	999.9	999.9	4.6	317.	20800.
50.0	-53.9	.000	999.9	999.9	20830.
999.9	999.9	999.9	4.1	333.	21120.
999.9	999.9	999.9	2.1	356.	21440.
999.9	999.9	999.9	1.0	034.	21760.
42.0	-54.3	.000	999.9	999.9	21950.
999.9	999.9	999.9	1.0	064.	22080.
39.0	-52.0	.000	1.0	267.	22430.
999.9	999.9	999.9	0.5	347.	22770.
36.0	-52.6	.000	999.9	999.9	22940.
999.9	999.9	999.9	0.5	007.	23110.
999.9	999.9	999.9	0.5	238.	23450.
999.9	999.9	999.9	0.5	229.	23790.
30.0	-48.2	.000	1.5	229.	24130.
999.9	999.9	999.9	1.5	207.	24430.
28.0	-47.0	.000	1.5	195.	24590.

DATA SETS = 118 (delete here if #RUNS = 1)

PRESS. (mbars)	TEMP. (C)	HUMID. (%/100)	WS (m/s)	WD (degrees)	ALTITUDE (meters)
834.9	22.4	.291	4.1	120.	1610.
828.0	20.2	.261	999.9	999.9	1680.
999.9	999.9	999.9	5.1	158.	1930.
778.0	15.5	.357	999.9	999.9	2200.
999.9	999.9	999.9	4.6	164.	2240.
750.0	12.0	.424	999.9	999.9	2520.
999.9	999.9	999.9	5.1	173.	2670.
700.0	6.9	.575	999.9	999.9	3100.
999.9	999.9	999.9	5.1	176.	3140.
999.9	999.9	999.9	5.1	186.	3560.
648.0	.8	.883	999.9	999.9	3720.
999.9	999.9	999.9	6.7	212.	3930.
615.0	-3.1	.963	999.9	999.9	4140.
999.9	999.9	999.9	7.7	243.	4230.
596.0	-4.2	.690	999.9	999.9	4390.
999.9	999.9	999.9	7.7	268.	4460.
579.0	-6.1	.714	999.9	999.9	4620.
999.9	999.9	999.9	7.7	279.	4680.
999.9	999.9	999.9	7.7	278.	4900.
554.0	-8.5	.664	999.9	999.9	4960.
999.9	999.9	999.9	7.2	274.	5140.
529.0	-10.1	.372	999.9	999.9	5320.
999.9	999.9	999.9	6.7	276.	5410.
513.0	-12.1	.411	999.9	999.9	5550.
999.9	999.9	999.9	6.7	280.	5690.
500.0	-13.8	.619	999.9	999.9	5750.
999.9	999.9	999.9	6.7	275.	5980.
483.0	-16.0	.532	999.9	999.9	6010.
999.9	999.9	999.9	5.7	266.	6260.
460.0	-17.2	.054	999.9	999.9	6380.
999.9	999.9	999.9	4.6	256.	6490.
452.0	-18.8	.304	999.9	999.9	6510.
444.0	-20.1	.492	999.9	999.9	6640.

999.9	999.9	999.9	4.6	256.	6740.
437.0	-20.7	.204	999.9	999.9	6760.
999.9	999.9	999.9	5.1	257.	6980.
410.0	-24.5	.247	5.1	270.	7230.
402.0	-25.5	.555	999.9	999.9	7370.
400.0	-25.7	.417	999.9	999.9	7410.
999.9	999.9	999.9	4.1	278.	7510.
389.0	-27.0	.041	999.9	999.9	7610.
999.9	999.9	999.9	3.6	266.	7800.
999.9	999.9	999.9	4.6	274.	8120.
999.9	999.9	999.9	4.6	270.	8430.
340.0	-35.2	.242	999.9	999.9	8560.
999.9	999.9	999.9	5.7	259.	8720.
999.9	999.9	999.9	6.2	264.	8990.
316.0	-39.7	.314	999.9	999.9	9070.
999.9	999.9	999.9	6.2	271.	9230.
300.0	-42.0	.000	999.9	999.9	9420.
999.9	999.9	999.9	8.2	280.	9470.
296.0	-42.6	.000	999.9	999.9	9510.
999.9	999.9	999.9	11.3	285.	9680.
283.0	-41.9	.000	999.9	999.9	9810.
999.9	999.9	999.9	14.4	283.	9930.
999.9	999.9	999.9	21.6	279.	10220.
999.9	999.9	999.9	23.2	281.	10500.
250.0	-46.0	.000	999.9	999.9	10650.
999.9	999.9	999.9	21.6	282.	10770.
237.0	-48.5	.000	999.9	999.9	11000.
999.9	999.9	999.9	24.7	278.	11020.
999.9	999.9	999.9	26.8	273.	11280.
999.9	999.9	999.9	27.3	271.	11540.
999.9	999.9	999.9	26.8	271.	11790.
999.9	999.9	999.9	27.3	273.	12050.
200.0	-53.5	.000	999.9	999.9	12100.
999.9	999.9	999.9	25.2	[illegible]	12320.
185.0	-55.8	.000	22.7	269.	12600.

999.9	999.9	999.9	25.7	266.	12880.
999.9	999.9	999.9	27.8	264.	13160.
999.9	999.9	999.9	27.3	262.	13430.
999.9	999.9	999.9	25.2	263.	13710.
150.0	-56.3	.000	999.9	999.9	13930.
999.9	999.9	999.9	24.7	265.	13990.
999.9	999.9	999.9	24.2	264.	14280.
999.9	999.9	999.9	25.7	263.	14570.
130.0	-59.6	.000	999.9	999.9	14830.
999.9	999.9	999.9	24.7	262.	14860.
999.9	999.9	999.9	23.2	264.	15160.
999.9	999.9	999.9	22.7	264.	15470.
117.0	-58.0	.000	999.9	999.9	15500.
999.9	999.9	999.9	20.6	264.	15730.
108.0	-59.4	.000	19.0	265.	16000.
999.9	999.9	999.9	17.0	259.	16300.
100.0	-58.3	.000	999.9	999.9	16480.
999.9	999.9	999.9	16.0	266.	16590.
999.9	999.9	999.9	14.4	264.	16870.
999.9	999.9	999.9	13.9	264.	17150.
999.9	999.9	999.9	13.4	269.	17430.
999.9	999.9	999.9	12.4	270.	17710.
999.9	999.9	999.9	10.3	266.	17980.
999.9	999.9	999.9	9.8	266.	18260.
999.9	999.9	999.9	9.3	266.	18540.
70.0	-61.0	.000	999.9	999.9	18710.
999.9	999.9	999.9	8.2	257.	18820.
999.9	999.9	999.9	8.2	261.	19100.
999.9	999.9	999.9	5.7	266.	19380.
62.0	-58.2	.000	999.9	999.9	19470.
60.0	-58.5	.000	4.6	262.	19670.
999.9	999.9	999.9	4.1	266.	19960.
999.9	999.9	999.9	4.6	290.	20240.
999.9	999.9	999.9	6.7	301.	20520.
999.9	999.9	999.9	4.6	317.	20800.

50.0	-53.9	.000	999.9	999.9	20830.
999.9	999.9	999.9	4.1	333.	21120.
999.9	999.9	999.9	2.1	356.	21440.
999.9	999.9	999.9	1.0	034.	21760.
42.0	-54.3	.000	999.9	999.9	21950.
999.9	999.9	999.9	1.0	064.	22080.
39.0	-52.0	.000	1.0	267.	22430.
999.9	999.9	999.9	0.5	347.	22770.
36.0	-52.6	.000	999.9	999.9	22940.
999.9	999.9	999.9	0.5	007.	23110.
999.9	999.9	999.9	0.5	238.	23450.
999.9	999.9	999.9	0.5	229.	23790.
30.0	-48.2	.000	1.5	229.	24130.
999.9	999.9	999.9	1.5	207.	24430.
28.0	-47.0	.000	1.5	195.	24590.

APPENDIX B

SUMMARY OF SUBROUTINES

Subroutine name; INTLGS

Description; INTLGS integrates the functions ZL, FL, CNSQL, CDSQL, CQSQL and EPSLNL over the slab

Inputs; P, T, Q, STBLTY, SHEAR, DQDZ, RI, THKSLB, ZLMIN, ZLMAX, ZLMEAN, SGMSH1, SGMST1

Output; PL, PF, PCNSQ, PCDSQ, PCQSQ, PEPSLN

Calls; SGMSHL, FNCTNL, GSSLGN

Called by; main program

Subroutine name; DATPRO

Description; DATPRO interpolates for missing rawinsonde data and calculates the weighted average and gradient values

Inputs; PRESS, TEMP, HUMID, WS, WD, Z, N, J, RUN

Output; PARY, TARY, QARY, STBARY, SHEARY, DQDZRY, RIARY, THKARY, N

Calls; INTER

Called by; main program

Subroutine name; INTER

Description; INTER performs a semi-log interpolation of the input variables

Inputs; A, B, C, D, NUMBER

Output; ANS

Calls; none

Called by; DATPRO

Subroutine name; FNCTNL

Description; FNCTNL computes the value of the turbulence parameters (F, Cn^2, and EPSILON) for a slab

Inputs; P, T, Q, STBLTY, SHEAR, DQDZ, RI, THKSLB, ZL, SGMSHR, SGMSTB, ZLMEAN

Output; FL, CNSQL, CDSQL, CQSQL, EPSLNL

Calls; BVRT

Called by; INTLGS

Subroutine name; BVRT

Description; BVRT controls the computation of the turbulence parameters using a bivariate model

Inputs; P, T, Q, STBLTY, SHEAR, DQDZ, RI, ZL, SGMSHR, SGMSTB

Output; F, CNSQ, CDSQ, CQSQ, EPSILN

Calls; INTGSH

Called by; FNCTNL

Subroutine name; INTGSH

Description; INTGSH integrates the input functions over SHEAR using Gaussian quadrature

Inputs; SHRSLB, STBSLB, ZL, SGMSHR, SGMSTB

Output; F, CN2, EPS

Calls; GSSLGN, FUNSHR, INTGS2, GSSLGR

Called by; BVRT

Subroutine name; FUNSHR

Description; FUNSHR computes a function, FTAU, from a Rice-Nakagami distribution of SHEAR's and a normal distribution of STABILITY

Inputs; TAU, TAUSLB

Output; FRNTAU

Calls; MBSS10

Called by; INTGSH

Subroutine name; INTGS2

Description; INTGS2 integrates the normal distribution function together with $(STABILITY)^2$ times the normal distribution function over STABILITY using Gaussian quadrature

Inputs; STBRIC, STBSLB, SGMSTB

Output; CDFSTB, CN2STB

Calls; STBINT, GSSLGR

Called by; INTGSH

Subroutine name; STBINT

Description; STBINT integrates two input functions over STABILITY using Gaussian quadrature

Inputs; STBMAX, STBMIN, STBSLB, SGMSTB, NSTB, NUMBER

Output; CDFSTB, CN2STB

Calls; GSSLGN, EXPNX

Called by; INTGS2

Subroutine name; GSSLGN

Description; GSSLGN calculates the abscissas and weights for Gaussian quadrature for limits from -1 to +1

Inputs; N

Output; X,W

calls; none

Called by; INTGSH, INTGLS

Subroutine name; GSSLGR

Description; GSSLGR calculates the abscissas and weights for Gaussian quadrature for limits from zero to infinity

Inputs; N

Output; X,W

Calls; none

Called by; INTGSH, INTGS2

Subroutine; MBSS10

Description; MBSS10 computes the value of the modified Bessel function of the first kind of order zero using the IMSL routine MMBSIO

Inputs; X

Output; ANSWER

Calls; MBSSIO (IMSL routine)

Called by; FUNSHR

Function name; EXPND

Description; EXPND computes the value of a normalized exponential distribution for ZL

Inputs; ZL, ZLMEAN

Output; EXPND

Calls; EXPNX

Called by; not in use presently, before modification, it was called in FNCTNL

Function name; SHRSGM

Description; SHRSGM computes the standard deviation of the SHEAR distribution

Inputs; SGMCON, P, T, ALPHA, STBLTY

Output; SHRSGM

Calls; none

Called by; main program

Function name; STBSGM

Description; STBSGM computes the standard deviation of the fluctuating part of STABILITY

Inputs; SHRSGM, STBLTY

Output; STBSGM

Calls; none

Called by; main program

Function name; SGMSHL

Description; SGMSHL computes the value of SGMSHL given SGMSH1 and ZL

Inputs; SGMSH1, ZL

Output; SGMSHL

Calls; none

Called by; INTLGS

Function name; PROB19

Description; PROB19 is intended to compute the probability function using polynomial approximation

Inputs; X

Output; PROB19

Calls; none

Called by; not presently in use, before modification, it was called in INTGSH

Function name; EXPNX

Description; EXPNX checks the input arguments to ensure they are within the operating limits of the computer. If they are not, it revalues them so that they are within limits to avoid underflows and overflows

Inputs; X

Output; EXPNX

Calls; none

Called by; STBINT, EXPFSH, EXPND

APPENDIX C

SAMPLE TURB2 DATAOUT FILE (#RUNS = 1)

SLAB#	MIDALT (M)	CN²
1	1645.00	0.6429895076D-16
2	1805.00	0.8525603886D-16
3	2065.00	0.1308713280D-16
4	2220.00	0.1840405935D-16
5	2380.00	0.1675688171D-16
6	2595.00	0.9289980295D-17
7	2885.00	0.9555537126D-17
8	3120.00	0.1028519061D-16
9	3350.00	0.1845121879D-17
10	3640.00	0.8746728887D-17
11	3825.00	0.2248982453D-16
12	4035.00	0.7019746893D-16
13	4185.00	0.1676746736D-15
14	4310.00	0.2076253792D-15
15	4425.00	0.1877315078D-15
16	4540.00	0.2996434361D-16
17	4650.00	0.2884930028D-16
18	4790.00	0.1875013105D-16
19	4930.00	0.2125610311D-16
20	5050.00	0.2529149526D-16
21	5230.00	0.2375408888D-16
22	5365.00	0.1080201618D-16
23	5480.00	0.1088445482D-16
24	5620.00	0.8812439910D-17
25	5720.00	0.9486586789D-17
26	5865.00	0.1078625192D-16
27	5995.00	0.1777040099D-16
28	6135.00	0.2783679743D-16

29	6320.00	0.3156149385D-16
30	6435.00	0.2373786114D-16
31	6500.00	0.2249937021D-16
32	6575.00	0.2985857815D-18
33	6690.00	0.1865800713D-16
34	6750.00	0.1937612712D-16
35	6870.00	0.1052763186D-16
36	7105.00	0.1490718353D-16
37	7300.00	0.1813311719D-16
38	7390.00	0.2892384730D-16
39	7460.00	0.2745028922D-16
40	7560.00	0.1685917667D-16
41	7705.00	0.1646131759D-16
42	7960.00	0.1687852523D-16
43	8275.00	0.8895951535D-17
44	8495.00	0.1192759561D-16
45	8640.00	0.1121599474D-16
46	8855.00	0.9671650870D-17
47	9030.00	0.1045068773D-16
48	9150.00	0.1359829831D-16
49	9325.00	0.3279598721D-16
50	9445.00	0.3337614124D-16
51	9490.00	0.1042557235D-15
52	9595.00	0.6504480124D-16
53	9745.00	0.4285484888D-16
54	9870.00	0.4098830537D-16
55	10075.00	0.3110753455D-15
56	10360.00	0.1411441978D-16
57	10575.00	0.1272454522D-16
58	10710.00	0.1333465354D-16
59	10885.00	0.5831460262D-16
60	11010.00	0.5737078697D-16
61	11150.00	0.3580049158D-16
62	11410.00	0.1080384642D-16
63	11665.00	0.9533808124D-17

64	11920.00	0.1521933891D-16
65	12075.00	0.1874242331D-16
66	12210.00	0.1619829771D-16
67	12460.00	0.2374495506D-16
68	12740.00	0.2598101284D-16
69	13020.00	0.1549131182D-16
70	13295.00	0.1054737223D-16
71	13570.00	0.1540170661D-16
72	13820.00	0.1251849086D-16
73	13960.00	0.1213451593D-16
74	14135.00	0.1147173704D-16
75	14425.00	0.5974197139D-18
76	14700.00	0.1379922626D-17
77	14845.00	0.1774158125D-17
78	15010.00	0.2883370486D-17
79	15315.00	0.1067950577D-16
80	15485.00	0.1216896389D-16
81	15615.00	0.9765411422D-17
82	15865.00	0.8095732044D-17
83	16150.00	0.1096763098D-16
84	16390.00	0.9651295968D-17
85	16535.00	0.9207633503D-17
86	16730.00	0.8188833993D-17
87	17010.00	0.6958387906D-17
88	17290.00	0.7090243292D-17
89	17570.00	0.6583973759D-17
90	17845.00	0.7582720669D-17
91	18120.00	0.5836168579D-17
92	18400.00	0.4927868104D-17
93	18625.00	0.5680862268D-17
94	18765.00	0.5600901504D-17
95	18960.00	0.4850331731D-17
96	19240.00	0.7716729501D-17
97	19425.00	0.6594158104D-17
98	19570.00	0.4023897304D-17

99	19815.00	0.3734642299D-17
100	20100.00	0.4261320896D-17
101	20380.00	0.4530608595D-17
102	20660.00	0.5746324061D-17
103	20815.00	0.4799269686D-17
104	20975.00	0.4589887089D-17
105	21280.00	0.4683289602D-17
106	21600.00	0.2859715419D-17
107	21855.00	0.2551690196D-17
108	22015.00	0.3095974497D-17
109	22255.00	0.3229411536D-17
110	22600.00	0.2199815305D-17
111	22855.00	0.2342476571D-17
112	23025.00	0.2279193328D-17
113	23280.00	0.2015465644D-17
114	23620.00	0.2460930328D-17
115	23960.00	0.2368559736D-17
116	24280.00	0.1883079643D-17
117	24510.00	0.1813421204D-17

APPENDIX D

COMPARISON OF RESULTS

Table 4 illustrates the corresponding values of $Cn^2(z)$ obtained from the NOAA program and the IBM model at the specified altitudes. The fourth column lists the percent difference in the IBM value relative to the NOAA value. The #RUNS was set at 1 which resulted in the MIDALT values being the same for both.

TABLE 4

Comparison of Program Output with #RUNS = 1

MIDALT (m)	NOAA Cn^2	MODEL Cn^2	% DIFFERENCE
1810.00	0.7908E-16	0.8526E-16	7.81%
2070.00	0.1029E-16	0.1309E-16	27.18%
2220.00	0.5189E-20	0.1840E-16	354574.06%
2380.00	0.5120E-20	0.1676E-16	327182.81%
2600.00	0.1081E-16	0.9290E-17	14.06%
2880.00	0.9127E-17	0.9556E-17	4.70%
3120.00	0.1409E-18	0.1029E-16	7199.64%
3350.00	0.2106E-18	0.1845E-17	776.13%
3640.00	0.3793E-18	0.8747E-17	2206.02%
3830.00	0.2510E-16	0.2249E-16	10.40%
4040.00	0.5660E-16	0.7020E-16	24.02%
4190.00	0.1529E-15	0.1677E-15	9.66%
4310.00	0.2080E-15	0.2076E-15	0.18%
4420.00	0.2071E-15	0.1877E-15	9.35%
4540.00	0.2880E-16	0.2996E-16	4.04%
4650.00	0.3446E-16	0.2885E-16	16.28%

4790.00	0.1726E-16	0.1875E-16	8.63%
4930.00	0.1942E-16	0.2126E-16	9.45%
5050.00	0.2452E-16	0.2529E-16	3.15%
5230.00	0.2288E-16	0.2375E-16	3.82%
5360.00	0.1090E-16	0.1080E-16	0.90%
5480.00	0.1029E-16	0.1088E-16	5.78%
5620.00	0.8983E-17	0.8812E-17	1.90%
5720.00	0.9177E-17	0.9487E-17	3.37%
5870.00	0.1063E-16	0.1079E-16	1.47%
6000.00	0.1619E-16	0.1777E-16	9.76%
6140.00	0.2705E-16	0.2784E-16	2.91%
6320.00	0.2939E-16	0.3156E-16	7.39%
6430.00	0.3485E-20	0.2374E-16	681043.31%
6500.00	0.3467E-20	0.2250E-16	648857.37%
6570.00	0.1168E-20	0.2986E-18	25463.84%
6690.00	0.1812E-16	0.1866E-16	2.97%
6750.00	0.1887E-16	0.1938E-16	2.68%
6870.00	0.1089E-16	0.1053E-16	3.33%
7100.00	0.1462E-16	0.1491E-16	1.96%
7300.00	0.1720E-16	0.1813E-16	5.43%
7390.00	0.1974E-16	0.2892E-16	46.52%
7460.00	0.1812E-16	0.2745E-16	51.49%
7560.00	0.1615E-16	0.1686E-16	4.39%
7700.00	0.8993E-17	0.1646E-16	83.05%
7960.00	0.9231E-17	0.1688E-16	82.85%
8280.00	0.6828E-17	0.8896E-17	30.29%
8500.00	0.1055E-16	0.1193E-16	13.06%
8640.00	0.8701E-17	0.1122E-16	28.90%
8850.00	0.5823E-17	0.9672E-17	66.09%
9030.00	0.5929E-17	0.1045E-16	76.26%
9150.00	0.1335E-16	0.1360E-16	1.86%
9330.00	0.3559E-16	0.3280E-16	7.85%
9440.00	0.3479E-16	0.3338E-16	4.06%
9490.00	0.9175E-16	0.1043E-15	13.63%
9600.00	0.5812E-16	0.6504E-16	11.91%

9750.00	0.4240E-16	0.4285E-16	1.07%
9870.00	0.5350E-16	0.4099E-16	23.39%
10070.00	0.5284E-15	0.3111E-15	41.13%
10360.00	0.1699E-16	0.1411E-16	16.93%
10570.00	0.1625E-16	0.1272E-16	21.70%
10710.00	0.1311E-16	0.1333E-16	1.71%
10880.00	0.5546E-16	0.5831E-16	5.15%
11010.00	0.5192E-16	0.5737E-16	10.50%
11150.00	0.3572E-16	0.3580E-16	0.23%
11410.00	0.1288E-16	0.1080E-16	16.12%
11670.00	0.1113E-16	0.9534E-17	14.34%
11920.00	0.1192E-16	0.1522E-16	27.68%
12080.00	0.1600E-16	0.1874E-16	17.14%
12210.00	0.1566E-16	0.1620E-16	3.44%
12460.00	0.2469E-16	0.2374E-16	3.83%
12740.00	0.2574E-16	0.2598E-16	0.94%
13020.00	0.1599E-16	0.1549E-16	3.12%
13290.00	0.1157E-16	0.1055E-16	8.84%
13570.00	0.1387E-16	0.1540E-16	11.04%
13820.00	0.1048E-16	0.1252E-16	19.45%
13960.00	0.8874E-17	0.1213E-16	36.74%
14140.00	0.8222E-17	0.1147E-16	39.52%
14430.00	0.9285E-17	0.5974E-18	93.57%
14700.00	0.8003E-17	0.1380E-17	82.76%
14850.00	0.9773E-17	0.1774E-17	81.85%
15010.00	0.1034E-16	0.2883E-17	72.11%
15310.00	0.8622E-17	0.1068E-16	23.86%
15480.00	0.1059E-16	0.1217E-16	14.91%
15610.00	0.9283E-17	0.9765E-17	5.20%
15870.00	0.7789E-17	0.8096E-17	3.94%
16150.00	0.1063E-16	0.1097E-16	3.18%
16390.00	0.9147E-17	0.9651E-17	5.51%
16540.00	0.8315E-17	0.9208E-17	10.74%
16730.00	0.7117E-17	0.8189E-17	15.06%

17010.00	0.5884E-17	0.6958E-17	18.26%
17290.00	0.6150E-17	0.7090E-17	15.29%
17570.00	0.5682E-17	0.6584E-17	15.87%
17840.00	0.6798E-17	0.7583E-17	11.54%
18120.00	0.4908E-17	0.5836E-17	18.91%
18400.00	0.4661E-17	0.4928E-17	5.73%
18620.00	0.5210E-17	0.5681E-17	9.04%
18760.00	0.5867E-17	0.5601E-17	4.54%
18960.00	0.5052E-17	0.4850E-17	3.99%
19240.00	0.6401E-17	0.7717E-17	20.56%
19420.00	0.4795E-17	0.6594E-17	37.52%
19570.00	0.3838E-17	0.4024E-17	4.84%
19810.00	0.4362E-17	0.3735E-17	14.38%
20100.00	0.4735E-17	0.4261E-17	10.00%
20380.00	0.4838E-17	0.4531E-17	6.35%
20660.00	0.4805E-17	0.5746E-17	19.59%
20820.00	0.3779E-17	0.4799E-17	27.00%
20970.00	0.3122E-17	0.4590E-17	47.02%
21280.00	0.3422E-17	0.4683E-17	36.86%
21600.00	0.2824E-17	0.2860E-17	1.26%
21850.00	0.2532E-17	0.2552E-17	0.78%
22020.00	0.3021E-17	0.3096E-17	2.48%
22250.00	0.3172E-17	0.3229E-17	1.81%
22600.00	0.2136E-17	0.2200E-17	2.99%
22860.00	0.1972E-17	0.2342E-17	18.79%
23030.00	0.2415E-17	0.2279E-17	5.62%
23280.00	0.2358E-17	0.2015E-17	14.53%
23620.00	0.2169E-17	0.2461E-17	13.46%
23960.00	0.2084E-17	0.2369E-17	13.65%
24280.00	0.1840E-17	0.1883E-17	2.34%

Table 5 illustrates the corresponding values of $Cn^2(z)$ obtained from the NOAA program and the IBM model at the specified altitudes. The fifth column lists the percent difference between the IBM value and the interpolated (semi-log) value from the NOAA data. Note that the different interpolation method (i.e. #RUNS = 2) produced different values for the MIDALT's thus making direct comparison impossible.

TABLE 5

Comparison of Program Output with #RUNS = 2

NOAA data		IBM data		% Difference
Cn^2	Alt. (m)	Cn^2	Alt. (m)	
		.6430E-16	1645.	
.7908E-16	1810.			
		.2272E-16	1940.	47.8
.1029E-16	2070.			
		.1671E-16	2360.	57.7
.1081E-16	2600.			
		.9325E-17	2810.	2.1
.9127E-17	2880.			
.1409E-18	3120.			
.2106E-18	3350.			
		.2361E-18	3410.	4.2
.3793E-18	3640.			
.2510E-16	3830.			
		.4002E-16	3930.	.7
.5660E-16	4040.			
.1529E-15	4190.			
		.1777E-15	4265.	5.2

.2080E-15	4310.			
.2071E-15	4420.			
		.5396E-16	4505.	32.8
.2880E-16	4540.			
.3446E-16	4650.			
.1726E-16	4790.	.1777E-16	4790.	2.9
.1942E-16	4930.			
.2452E-16	5050.			
		.2397E-16	5140.	1.1
.2288E-16	5230.			
.1090E-16	5360.			
		.1068E-16	5435.	1.5
.1029E-16	5480.			
.8983E-17	5620.			
		.8406E-17	5650.	7.0
.9177E-17	5720.			
.1063E-16	5870.			
		.1101E-16	5880.	.4
.1619E-16	6000.			
.2705E-16	6140.			
		.2890E-16	6195.	4.0
.2939E-16	6320.			
		.2362E-16	6445.	7.4
		.2990E-18	6575.	98.6
.1812E-16	6630.			
		.1860E-16	6700.	1.9
.1887E-16	6750.			
.1089E-16	6870.			
		.1142E-16	6995.	11.3
.1462E-16	7100.			
.1720E-16	7300.	.1820E-16	7300.	5.8
.1974E-16	7390.	.2887E-16	7390.	46.3
.1812E-16	7460.			
		.1883E-16	7510.	9.9
.1615E-16	7560.			

.8993E-17	7700.			
.9231E-17	7960.			
		.7248E-17	8085.	12.4
.6828E-17	8280.			
.1055E-16	8500.			
.8701E-17	8640.			
		.5582E-17	8815.	11.6
.5823E-17	8850.			
.5929E-17	9030.			
.1335E-16	9150.			
		.1874E-16	9245.	25.4
.3559E-16	9330.			
.3479E-16	9440.			
		.5349E-16	9465.	39.0
.5812E-16	9600.			
		.5137E-16	9660.	.8
.4240E-16	9750.			
.5350E-16	9870.			
		.3826E-16	10230.	43.6
.1699E-16	10360.			
.1625E-16	10570.			
.1311E-16	10710.			
		.1586E-16	10825.	62.1
.5546E-16	10880.			
.5192E-16	11010.			
.3572E-16	11150.			
.1288E-16	11410.			
		.1223E-16	11550.	2.4
.1113E-16	11670.			
.1192E-16	11920.			
.1600E-16	12080.			
.1566E-16	12210.			
		.1899E-16	12350.	8.5
.2469E-16	12460.			
.2574E-16	12740.			

.1599E-16	13020.			
		.1148E-16	13265.	4.3
.1157E-16	13290.			
.1387E-16	13570.			
.1048E-16	13820.			
.8874E-17	13960.			
.8222E-17	14140.			
		.8152E-17	14380.	10.4
.9285E-17	14430.			
.8003E-17	14700.			
.9773E-17	14850.			
.1034E-16	15010.			
		.9776E-17	15165.	3.4
.8622E-17	15310.			
.1059E-16	15480.			
.9283E-17	15610.			
		.8831E-17	15750.	4.4
.7789E-17	15870.			
.1063E-16	16150.			
		.8503E-17	16240.	15.6
.9147E-17	16390.			
.8315E-17	16540.			
.7117E-17	16730.			
.5884E-17	17010.			
.6150E-17	17290.			
.5682E-17	17570.			
		.5776E-17	17595.	.1
.6798E-17	17840.			
.4908E-17	18120.			
.4661E-17	18400.			
.5210E-17	18620.			
.5867E-17	18760.			
.5052E-17	18960.			
		.5693E-17	19090.	.2
.6401E-17	19240.			

.4795E-17	19420.			
.3838E-17	19570.	.4007E-17	19570.	4.4
.4362E-17	19810.			
.4735E-17	20100.			
		.4260E-17	20250.	11.1
.4838E-17	20380.			
.4805E-17	20660.			
.3779E-17	20820.			
.3122E-17	20970.			
.3422E-17	21280.			
		.3058E-17	21390.	4.7
.2824E-17	21600.			
.2532E-17	21850.			
.3021E-17	22020.			
		.3190E-17	22190.	1.8
.3172E-17	22250.			
.2136E-17	22600.			
		.2106E-17	22685.	1.1
.1972E-17	22860.			
.2415E-17	23030.			
.2358E-17	23280.			
		.2285E-17	23535.	3.4
.2169E-17	23620.			
.2084E-17	23960.			
.1840E-17	24280.			
		.1852E-17	24360.	

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